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A Review of Innovative CO₂ Reduction Methods for Climate Change Mitigation

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ABSTRACT

This review highlights the urgent need for innovative methods to reduce and capture carbon dioxide (CO₂), a crucial step in tackling climate change. Over the past century, human activities have raised atmospheric CO₂ levels from 310 ppm to 415 ppm, resulting in global warming and significant climate disruptions. The paper comprehensively discusses various technologies for carbon capture, including membrane-based systems, oxy-fuel combustion, chemical looping combustion (CLC), and cryogenic carbon capture (CCC). Membrane-based systems show strong potential for cost-effective, scalable carbon capture. Polymeric membranes are cheap but limited by selectivity and durability, while inorganic ones offer better stability and performance. Mixed matrix membranes (MMMs) combine these strengths, improving efficiency as material compatibility advances. Other approaches include oxy-fuel combustion, which simplifies CO₂ capture but demands high energy for air separation; chemical looping combustion (CLC), which avoids NO_x emissions but requires durable materials; and cryogenic carbon capture (CCC), which yields pure CO₂ but is energy-intensive. Improving heat and energy management could enhance these methods. Ultimately, no single solution will suffice—combining technologies, fostering industrial collaboration, and supporting policies like carbon pricing are essential to achieve substantial CO₂ reductions.

Keywords: CO₂ reduction; carbon capture; Membrane; carbon chemical looping; climate change

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1. INTRODUCTION

Carbon dioxide (CO₂) is a gas that is both colorless and odorless gas found in the Earth's atmosphere. Natural processes, including the respiration of humans and animals, the combustion of various materials, and volcanic eruptions, contribute

to CO₂ emissions [1]. However, human activities such as the combustion of fossil fuels, chemical processing, and deforestation significantly impact CO₂ emissions [2]. As a result of these actions, the level of CO₂ has increased from 310ppm to 415ppm over the past

century [3], a trend that urgently needs to be addressed to prevent further damage to our planet. The urgency of this issue cannot be overstated, and immediate action is required to mitigate the effects of climate change. An increase in greenhouse gas concentrations is directly linked to the intensification of the greenhouse effect, which influences the wavelength of solar radiation within the Earth's atmosphere and accelerates the conversion of ultraviolet light into infrared light [4]. Because the energy from infrared light is primarily released as heat, the buildup of infrared light in the atmosphere would also raise the atmosphere's temperature.

The greenhouse effect, a natural process that warms the Earth's surface, is the primary driver of climate change across various regions of the Earth [5]. However, the intensification of this effect due to increased greenhouse gas concentrations, particularly carbon dioxide (CO₂), is a significant concern. This intensification leads to significant fluctuations in climate, which can lead to droughts, floods, storms, and hurricanes, affecting terrestrial and marine ecosystems, human societies, and their habitats [6]. These dramatic weather changes disrupt the livability of both rural and urban areas, resulting in population shifts as individuals are forced to relocate in response to the impacts of droughts, floods, and storms [7]. The most significant contributor to the greenhouse effect is carbon dioxide (CO₂). Human activities, such as burning fossil fuels and deforestation, have increased the concentration of CO₂ in the atmosphere far beyond natural levels [8]. This excess CO₂ traps more heat, leading to global warming and climate change. While the greenhouse effect is essential for life on Earth, its intensification due to human-caused CO₂ emissions is a primary environmental concern. Therefore, measures to reduce CO₂ concentrations must be implemented to lessen the negative impacts of greenhouse gases on the environment [9].

This paper delves into various advanced CO₂ reduction and capture methods, each with unique advantages and limitations. Among these, membrane-based approaches stand out with their potential to revolutionize CO₂ reduction. These innovative systems, employing selective membranes, promise a more efficient and cleaner future. The selectivity of these membranes, based on variations in the size,

shape, and interactions of gas molecules with the membrane structure, offers hope for a more sustainable and environmentally friendly future. In CO₂ capture, three primary types of membranes are employed. The most commonly used polymer membranes are recognized for their low cost, ease of production, and favorable CO₂ permeability. However, their selectivity presents a considerable challenge, as they often struggle to effectively differentiate CO₂ from other gases [10]. In contrast, inorganic membranes, made from ceramic or metallic materials, boast high thermal and chemical stability, making them suitable for high-temperature applications. However, their cost and brittleness are notable drawbacks. Finally, mixed matrix membranes (MMMs) offer a hybrid solution combining both membrane types' advantages [11]. By incorporating inorganic fillers into a polymer matrix, MMMs enhance the processability of polymers while improving CO₂ selectivity.

While membrane-based CO₂ capture technology has gained considerable attention due to its numerous advantages, it is essential to acknowledge the challenges that come with it. In contrast to traditional methods, such as amine scrubbing, membrane technology presents potential energy savings. The modular design of these membranes enhances scalability and increases their application flexibility. Furthermore, the cost-effective production of polymer membranes can contribute to lower capture expenses. The overall reduction in energy consumption associated with this technology further helps diminish the carbon footprint of the capture process. However, challenges such as membrane durability and resilience persist, underscoring the need for continuous innovation and problem-solving in CO₂ reduction. Oxy-fuel combustion technology is a significant method for reducing CO₂ emissions, known for substantially minimizing emissions at the source. While fossil fuel-based power plants remain vital to the energy supply, they also significantly contribute to CO₂ emissions. Oxy-fuel combustion replaces air with nearly pure oxygen, offering an effective solution for emission reduction [12]. The fundamental principle involves substituting regular air—about 78% nitrogen—with oxygen that is approximately 95% pure for combustion. Although this change may seem

straightforward, it brings substantial advantages. Air separation units (ASUs) break down air into its components to provide the necessary oxygen for combustion. In this process, fuels such as coal, natural gas, or biomass react with oxygen to produce heat. This method results in flue gas containing roughly 90% CO₂, a concentration significantly higher than the typical 15% in conventional air combustion [13]. This elevated CO₂ concentration greatly facilitates the capture and reduction process.

An innovative method for CO₂ mitigation is chemical looping combustion (CLC), which enables combustion to occur without direct contact between fuel and air, thereby creating new opportunities for effective CO₂ control and separation [14]. In CLC, the oxygen necessary for combustion is supplied by an oxygen carrier that cycles between oxidation and reduction reactors. The fuel interacts with this oxygen carrier, resulting in the production of CO₂ and water.

2. METHODOLOGY

Four major databases were used to collect critical data for this paper: Scopus, ScienceDirect, Google Scholar, and Web of Science. Regarding keywords, there are five main combinations used for searching in the mentioned databases, which are as follows:

- “membrane “AND “oxy-fuel “AND “chemical looping combustion” AND “Cryogenic” AND “carbon dioxide”
- “membrane “AND “oxy-fuel “AND “chemical looping combustion” AND “Cryogenic” AND “Environment”
- “membrane “AND “oxy-fuel “AND “chemical looping combustion” AND “Cryogenic” AND “Climate change”

3. RESULTS AND DISCUSSION

3.1 Membranes for CO₂ Capture

This study's comprehensive analysis of three main categories of membranes used for CO₂ capture is significant. Each category will be thoroughly

One of the primary advantages of CLC is its ability to generate a CO₂-rich stream directly, which minimizes the need for additional separation processes and reduces energy consumption and costs. This technology is currently the focus of extensive research to optimize its efficacy for greenhouse gas mitigation [15]. Cryogenic technology is an effective method for separating CO₂ from gas streams. By lowering the temperature to extreme levels, CO₂ can be condensed into either a liquid or solid state, facilitating efficient separation from other gases [16,18]. These cryogenic processes are known for producing highly pure CO₂, making them particularly advantageous for industrial applications and carbon storage [17-21]. Although the energy consumption can be significant, the benefits—including eliminating chemical reagents, the potential for direct storage, and the efficiency at high CO₂ concentrations—render it a viable option for mitigating greenhouse gas emissions.

- “membrane “AND “oxy-fuel “AND “chemical looping combustion” AND “Cryogenic” AND “liquid sorbent”
- “membrane “AND “oxy-fuel “AND “chemical looping combustion” AND “Cryogenic” AND “Solid sorbent”

Most of the publications were journal articles. However, a wide range of publications was reviewed to cover a wide diversity of information. After gathering information from various sources, the data was summarized, concluded, and reported.

discussed below, providing valuable insights for the reader.

3.1.1. Polymeric Membranes

Polymeric membranes are thin layers composed of various polymeric materials such as polyethylene (PE), polyimide (PI), and polyethylene oxide (PEO). These polymers are chosen for their ability to create selective barriers that allow the passage of specific molecules while blocking others. For CO₂ capture, the membrane must selectively permit the passage of CO₂ while preventing the infiltration of other gases like nitrogen, which is a significant component of air.

Selective CO₂ Passage Mechanisms:

1. **Molecular Size Effect:** Smaller molecules like CO₂ traverse faster through the polymer network's free volume or pores than larger molecules.
2. **Preferential Interactions:** Certain polymers exhibit a stronger affinity for CO₂ due to specific interactions with the polymer chains, which may include hydrogen bonds or dipole-dipole forces.

Unique Advantages of Polymeric Membranes for CO₂ Capture: Polymeric membranes offer several unique advantages for CO₂ capture, making them a key option in CO₂ capture technologies. These advantages include cost-effectiveness, ease of fabrication, adjustable properties, and their lightweight and flexible nature.

- **Cost-Effectiveness:** Polymeric membranes are generally less expensive than ceramic or metallic alternatives, making them viable for large-scale CO₂ capture.
- **Ease of Fabrication:** They can be produced through various methods such as casting, spinning, and extrusion, enabling large-scale and customizable production.
- **Adjustable Properties:** These polymers' chemical structure and process conditions can

be tailored to optimize CO₂ permeability and selectivity, adapting the membrane to different capture conditions.

- **Lightweight and Flexible:** Their lightweight and flexible nature facilitates the design and installation of membrane modules for CO₂ capture systems.

Challenges of Polymeric Membranes for CO₂ Capture:

- **Limited Selectivity:** While they provide some CO₂ separation, further enhancements are often necessary to optimize efficiency. This may lead to increased passage of other gases, reducing CO₂ stream purity.
- **Durability Issues:** Polymeric membranes may degrade under harsh operational conditions, such as high temperatures or exposure to chemical contaminants in flue gases, necessitating frequent replacements.
- **Plasticization:** Certain polymers may swell upon contact with CO₂, compromising their selective properties. This requires careful material selection and process condition adjustments.
- **Fouling:** Accumulating impurities on the membrane surface can decrease gas permeability over time, necessitating regular cleaning or pre-treatment of the gas stream.

These characteristics and challenges have made polymeric membranes a key option in CO₂ capture technologies. Importantly, ongoing research is dedicated to enhancing their efficiency and addressing existing limitations, demonstrating the dynamic nature of this field.

3.1.2. Inorganic Membranes

Due to their superior thermal and chemical stability compared to polymeric membranes, inorganic membranes are considered attractive for CO₂ capture under harsh conditions. Unlike polymeric membranes

made from organic compounds, inorganic membranes are constructed from ceramics and metals, including zeolites, silica, alumina, and metal oxides. These materials form highly structured crystalline lattices

with well-defined pores that enable precise control over gas permeability and selectivity.

Advantages of Inorganic Membranes:

- **High Thermal Stability:** They can endure high temperatures in industrial flue gases, maintaining performance where polymeric membranes may fail.
- **Superior Chemical Resistance:** Inorganic membranes exhibit high resistance to corrosive chemicals such as SO_x and NO_x, making them suitable for gas streams containing these pollutants.
- **Higher Selectivity:** They often provide better CO₂ selectivity than many polymeric membranes, resulting in higher-purity CO₂ streams and potentially reducing downstream processing costs.
- **Extended Lifespan:** Their robust structure offers increased longevity under challenging operational environments.

3.1.3. Mixed Matrix Membranes (MMMs)

Mixed matrix membranes (MMMs) combine the benefits of both polymeric and inorganic membranes. These membranes typically have a continuous polymer matrix embedded with dispersed inorganic fillers such as zeolites, metal oxides, or metallic nanoparticles. The careful selection of polymer and filler materials is crucial to optimizing the performance of MMMs.

Synergistic Effects in MMMs:

- **Improved Selectivity:** Inorganic fillers with well-defined pore structures and surface characteristics can enhance CO₂ selectivity when dispersed within the polymer matrix.
- **Increased Permeability:** Although inorganic materials generally exhibit lower permeability, their inclusion in MMMs can create additional pathways that facilitate gas transport, enhancing overall gas permeability.

Advantages of MMMs for CO₂ Capture:

Challenges of Inorganic Membranes:

- **High Production Costs:** The manufacturing process for inorganic membranes is more expensive than that for polymeric ones, posing an economic barrier to broader applications.
- **Brittleness:** Certain inorganic membranes, especially ceramic ones, are prone to mechanical damage and require careful handling.
- **Lower Permeability:** Inorganic membranes generally exhibit lower gas permeability than polymeric membranes, which may limit CO₂ capture capacity. Optimized membrane design and precise operational conditions are necessary to overcome this limitation.

Despite these challenges, inorganic membranes remain promising for CO₂ capture in severe industrial conditions. Ongoing efforts to enhance their properties and broaden their practical applications provide hope for their future role in CO₂ capture.

- **Adjustable Properties:** The properties of MMMs can be tailored by selecting different polymer matrices and filler types and controlling their distribution and concentration.
- **Enhanced Durability:** Inorganic fillers can bolster the polymer matrix's mechanical strength and chemical resistance compared to pure polymeric membranes.
- **Cost Efficiency:** MMMs require fewer expensive inorganic materials, making them more cost-effective than fully inorganic membranes.
- **High Processability:** The presence of a polymer matrix allows for the use of well-established membrane fabrication techniques.

Challenges and Considerations for MMM Development:

- **Uniform Filler Distribution:** A homogeneous distribution of inorganic fillers is essential for optimal performance. Poor distribution can hinder gas transport and reduce efficiency.
- **Interfacial Compatibility:** Ensuring good adhesion between the polymer and inorganic filler is critical. Poor compatibility may result in interfacial voids, reducing selectivity and potentially causing filler detachment.

Balancing Selectivity and Permeability: A significant challenge is to achieve an optimal balance between CO₂ selectivity and overall gas permeability. Although inorganic fillers enhance selectivity, they

3.2. Oxy-Fuel Combustion

Oxy-fuel combustion, known for reducing flue gas volume and increasing CO₂ concentration, is an attractive CO₂ capture and separation method. The absence of nitrogen results in a flue gas stream with a higher CO₂ concentration, which requires less energy for CO₂ stabilization technologies such as chemical and physical absorption. Additionally, this absence minimizes NO_x emissions typically associated with air combustion. The lack of nitrogen also allows for higher combustion temperatures, potentially improving the efficiency of boilers and energy production. This technology is compatible with various fossil fuels and even biomass.

However, oxy-fuel combustion faces challenges such as the high cost of oxygen separation units (ASUs) and necessary modifications to existing power plants. Optimizing energy use in the air separation process is crucial for overall efficiency. Additionally, handling pure oxygen requires specific safety protocols to mitigate fire hazards.

Research and development are ongoing to address these challenges. Efforts include developing heat-resistant materials for boilers and turbines specific to this process. Furthermore, cost-effective methods for retrofitting existing power plants and CO₂ capture tailored to oxy-fuel combustion are being explored. Pilot projects are underway to assess economic and technical aspects and provide real-world data for further improvements.

can sometimes decrease permeability, necessitating careful material and design choices. Current research focuses on developing innovative fillers with tailored pore structures and surface functionalities, investigating new polymer matrices with a natural affinity for CO₂, and employing surface modification techniques to improve compatibility. Computational modeling also predicts MMM behavior and guides design and optimization efforts. These advancements aim to enhance the industrial feasibility of MMMs for CO₂ capture and ensure that they contribute effectively to carbon management strategies, inspiring confidence in their potential role in the future.

The future of oxy-fuel combustion looks promising as part of carbon capture and storage (CCS) technologies, which securely store captured CO₂ underground. Integrating oxy-fuel combustion with current technologies can reduce costs and enhance efficiency. For instance, partial use of oxy-fuel combustion in flue gas processing while utilizing air combustion for the remainder is feasible.

Combining this technology with advanced power generation cycles, such as the oxy-fuel OCO cycle, can improve efficiency and reduce CO₂ emissions. In these cycles, a separate oxygen stream is used for combustion and flue gas oxidation, producing a purer CO₂ stream.

Supporting renewable energy, oxy-fuel combustion can help balance grid loads and ensure a stable power supply, especially when integrated with renewable energy storage systems, contributing to a more resilient, low-carbon grid.

Collaborative efforts among governments, research institutions, energy companies, and equipment manufacturers are essential for fully utilizing this technology. Public-private partnerships can accelerate research and reduce costs. Additionally, implementing carbon pricing mechanisms and financial incentives for CCS projects can drive investment in this technology. Public awareness campaigns highlighting the benefits of oxy-fuel combustion and addressing safety concerns are also crucial.

3.3. Chemical Looping Combustion (CLC)

Chemical looping combustion (CLC) is an innovative approach for combustion and carbon capture, utilizing oxygen carriers based on metal oxides to transfer oxygen between two main reactors: the air reactor and the fuel reactor. Unlike conventional methods that use air as the oxygen source, CLC introduces oxygen directly via these carriers. In this process, metal oxide particles react with air in the air reactor, reoxidizing to prepare for the fuel reactor. The oxidized carrier is then transferred to the fuel reactor, releasing oxygen to react with the incoming fuel, producing a concentrated CO₂ stream without nitrogen dilution.

CLC presents significant advantages by eliminating complex air separation processes and providing a high-purity CO₂ stream with lower energy consumption, making its capture more straightforward and economical. This method is adaptable to various fuels, from coal and natural gas to biomass, offering high flexibility. Environmentally, CLC's avoidance of NO_x emissions is beneficial and provides higher thermal efficiency.

Nonetheless, CLC faces its own set of challenges. Developing oxygen carrier materials with high durability and performance at high temperatures is crucial. Additionally, designing reactors that ensure effective thermal management and optimal gas-solid contact is critical to achieving efficient CLC performance. Adapting this technology to existing infrastructure requires detailed engineering studies and economic assessments.

Intensive research is underway to overcome these obstacles and advance CLC. Developing new

materials with enhanced properties and methods for process efficiency improvements suggests a promising future for CLC. This technology could become integral to CCS systems, where captured CO₂ is safely stored underground, and CLC integration with air-based power plants presents a cost-effective solution for CO₂ reduction.

Moreover, combining CLC with advanced power cycles, such as oxy-fuel OCO combustion, could enhance performance and reduce emissions. OCO cycles utilize separate oxygen flows for combustion and flue gas oxidation, producing a purer CO₂ output.

With the expansion of renewable energy, CLC can support a stable power supply and grid load management, especially when paired with renewable energy storage systems, fostering a sustainable, low-carbon energy network. Realizing CLC's full potential will require coordinated efforts among governments, research bodies, energy companies, and manufacturers to accelerate R&D and pilot projects. Lowering costs through material development, optimized design, and carbon pricing mechanisms, alongside financial incentives, could bolster investment in CLC.

Finally, public education and addressing safety concerns are essential for broader acceptance of CLC. By overcoming challenges and fostering collaboration, CLC can contribute to significant CO₂ reductions from fossil fuel-based power plants, promoting a more sustainable future and improving environmental quality.

3.4. Cryogenic Carbon Capture (CCC)

Cryogenic Carbon Capture (CCC) is an emerging and efficient method for CO₂ separation. It leverages extremely low temperatures to exploit the distinct behaviors of gases, particularly CO₂ and nitrogen, under such conditions. The process is designed in multiple stages to optimize CO₂ capture and separation.

Process Stages in CCC:

1. Pre-Treatment: The flue gas stream, comprising CO₂, nitrogen, and other impurities, undergoes pre-treatment to remove contaminants that could harm subsequent stages and impact process efficacy.
2. Cooling and Compression: The treated gas is cooled using multi-stage compressors and high-efficiency heat exchangers to temperatures ranging from -80°C to -140°C.

This cooling facilitates the phase separation needed for CO₂ isolation.

3. Phase Separation: The cooled gas mixture enables CO₂, which has a higher critical temperature than nitrogen, to condense into a liquid phase while nitrogen remains gaseous. This phase difference allows effective CO₂ separation from the gas stream.
4. CO₂ Purification: The liquid CO₂ may undergo additional purification to achieve desired purity levels, using technologies such as Pressure Swing Adsorption (PSA) to remove residual gases.
5. Storage or Utilization: The purified CO₂ can be utilized in enhanced oil recovery (EOR) or stored securely in geological formations as part of Carbon Capture and Storage (CCS) strategies.

Advantages of CCC:

- High Capture Efficiency: CCC can capture over 90% of CO₂, resulting in highly concentrated CO₂ streams suitable for further use or storage.

4. COCLUSION

The investigation into various innovative CO₂ reduction and capture methods underscores the critical need for advancing technologies to mitigate climate change. Each method—from membrane-based separation and oxyfuel combustion to chemical looping and cryogenic carbon capture—demonstrates unique strengths and challenges, reflecting the complex nature of CO₂ mitigation efforts. The diversity of these approaches highlights the necessity of adopting a multifaceted strategy that leverages their individual and combined benefits.

Membrane technology, for instance, offers modularity and cost-effectiveness, particularly with polymeric and mixed matrix membranes. Polymeric membranes are known for their adaptability and low production costs, making them attractive for large-scale applications. However, challenges such as limited selectivity and issues related to plasticization under operational conditions demand further advancements in material science. Mixed matrix membranes

- Adaptability: This method is compatible with various fuel sources, making it applicable across different industries.
- Integration Capability: CCC can be incorporated into existing industrial and power plant infrastructures with minimal modifications.
- Energy Efficiency: CCC's energy efficiency has improved significantly due to advancements in cryogenic techniques and thermal integration strategies.

Challenges and Development Needs:

- High Initial Costs: The capital expenditure for cryogenic equipment and infrastructure is substantial.
- Energy Demand: The cooling and compression stages require significant energy input despite improvements.
- Operational Complexity: Running CCC systems requires cryogenic technology and gas handling expertise, adding to the operational intricacies.

(MMMs), which blend polymeric and inorganic components, present a potential solution by enhancing CO₂ selectivity while maintaining flexibility. Nonetheless, achieving uniform filler distribution and optimal interfacial compatibility between materials remains a complex task requiring innovative design and fabrication techniques.

Oxy-fuel combustion stands out for its ability to produce high-purity CO₂ streams directly, significantly reducing the complexity of downstream separation. This process, which substitutes air with nearly pure oxygen, minimizes nitrogen dilution and enhances CO₂ capture efficiency. However, the energy-intensive nature of air separation units (ASUs) and the substantial costs associated with retrofitting existing power plants present significant barriers. Addressing these issues will involve developing more energy-efficient ASU technologies and exploring novel integration methods that lower operational expenses. Moreover, the potential for oxy-fuel

combustion combined with renewable energy sources can enhance its sustainability and reduce the overall carbon footprint of power generation.

Chemical looping combustion (CLC) shows exceptional promise due to its inherent efficiency and ability to produce a concentrated CO₂ stream. By utilizing metal oxide particles as oxygen carriers, CLC bypasses the need for direct contact between fuel and air, streamlining the CO₂ capture process and eliminating the formation of nitrogen oxides (NO_x). However, for CLC to be viable on an industrial scale, further research is necessary to develop oxygen carriers with excellent thermal stability, durability, and reactivity. The design and engineering of reactors that optimize gas-solid interactions and thermal management are also critical for maximizing performance and economic feasibility.

Cryogenic carbon capture (CCC) effectively separates CO₂ from flue gases by cooling them to extremely low temperatures, allowing CO₂ to condense while other gases remain gaseous. This method is particularly advantageous for applications that require high-purity CO₂ streams, such as enhanced oil recovery (EOR) and carbon storage. Nevertheless, the high energy demand of the cooling and compression stages poses a significant challenge. To improve CCC's economic feasibility, future developments should focus on advanced heat exchange technologies, better thermal integration strategies, and exploring the use of renewable energy to power the process.

Future research must prioritize overcoming these technological hurdles through targeted advancements in material development, process optimization, and enhanced integration with renewable energy systems. Collaborative efforts between governments, industry

stakeholders, research institutions, and technology developers are essential for scaling these technologies effectively and ensuring their real-world applicability. Public policies encouraging innovation and investment, including carbon pricing mechanisms, tax incentives, and grants for research and pilot projects, will be pivotal in driving the widespread adoption of these solutions.

Public awareness and education are vital to fostering acceptance and support for CO₂ reduction initiatives. Transparent communication about the benefits and challenges of each technology, coupled with initiatives that address potential safety and environmental concerns, can help build trust and encourage more proactive community engagement. Pilot programs and demonstration projects can serve as valuable tools for showcasing the practical benefits and addressing operational issues in real-world settings.

This comprehensive assessment of CO₂ capture methods highlights that while no single technology provides a complete answer, a combination of approaches tailored to specific applications can collectively address the global challenge of carbon emissions. Integrating these methods with existing infrastructure and future power systems will be crucial for maximizing their impact. Continued advancements, strategic partnerships, and supportive policies will enable the effective deployment of these technologies, leading to significant reductions in atmospheric CO₂ levels and contributing to global efforts to mitigate the impacts of climate change. In this way, pursuing technological innovation, backed by collaborative global action, holds the potential to pave a sustainable path forward.

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